The development and application of centrifugal flotation systems in wastewater treatment

Miroslav Colic and Wade Morse

Clean Water Technology Inc.,
6860 Cortona Dr., Building A, Goleta, CA 93117, USA
Fax: (805) 685 9105 E-mail: mcolic@cleanwatertech.com
E-mail: wmorse@cleanwatertech.com

Jan D. Miller*

Department of Metallurgical Engineering,
University of Utah, 135 S. 1460 E. Rm 412,
Salt Lake City, UT 84112-0114, USA
Fax: (801) 581-4937 E-mail: jdmiller@mines.utah.edu
*Corresponding author

Abstract: Flotation as a wastewater treatment technique is designed to remove all particles generally encountered as very fine emulsions, suspended solids, and colloids from wastewater. Historically, Dissolved Air Flotation (DAF) has been used to achieve this removal. More recently, other flotation techniques such as induced air, electro, cavitational, and Centrifugal Flotation Systems (CFS) have been applied in wastewater treatment. CFS use centrifugal force to enhance mixing of particles and bubbles with treatment chemicals and accelerate solid/liquid separation. In the most recent design, centrifugal hydrocyclone mixing was combined with small dissolved-air flotation bubbles leading to the development of the hybrid, dissolved-air centrifugal flotation.

Keywords: wastewater treatment; centrifugal flotation; liquid cyclone mixing; hybrid centrifugal dissolved-air flotation; ASH; BAF; GEM; FF.

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Biographical notes: Miroslav Colic received his PhD in Applied Surface Science from the University of California, Berkeley, in 1994. He received postdoctoral training at the University of California, Santa Barbara. His research interests are applied colloid and polymer science, coagulation, flocculation, flotation, mixing, sedimentation, and new technology development. He has published 40 papers and co-authored three patents. He has co-chaired two conferences, and organised sessions at three meetings. He is currently chief scientist/research director at Clean Water Technology Inc.

Wade Morse currently holds the position of Chief Officer of Operations at Clean Water Technology, Inc. His research is in the area of design and development of new technologies for centrifugal mixing, coagulation, flocculation, aeration and flotation. He is also active in system and auxiliary components design. He has co-authored eight papers and dozens of patents in the USA and abroad.

Jan D. Miller is Chair and the Ivor D. Thomas Professor of Metallurgical Engineering at the University of Utah. He received his BS from the Pennsylvania State University, MS and PhD from the Colorado School of Mines. At the University of Utah, he has devoted over 30 years to undergraduate and graduate instructions. His research covers mainly the areas of mineral processing and coal preparation, specialising in particulate systems, aqueous solution chemistry, and colloid and surface chemistry. He is the recipient of numerous honours and awards, and in 1993 was elected to the National Academy of Engineering.

1 Introduction

Froth flotation and other processes in the mineral industry are designed to maximise separation of one particle type from another or improve mineral concentration. On the other hand, flotation processes in water and wastewater treatment are designed to remove all suspended particles, colloids, emulsions, and even some ions or soluble organics that can be precipitated or adsorbed on suspended solids. In this case, the process is optimised by the maximum recovery of cleaned water with the lowest concentration of contaminants. It is also often desired that the recovered sludge contain a high percentage of solids. Such solids can sometimes be recycled and reused. The design features and operating conditions of flotation equipment used for this purpose must be modified accordingly. It is evident that the processes causing water loss to the froth phase or migration of solids to the water phase must be minimised and appropriate conditions established for complete particle recovery. Recent reviews summarise new developments in flotation as a wastewater treatment technique (Jameson, 1999; Rubio et al., 2002).

It is particularly common to encounter wastewater that contains a mixture of suspended particles and stable oil emulsions. It is difficult to remove oily contaminants from wastewater and other natural and industrial systems containing oil. Oil can be present as a non-dispersed surface layer, usually floating at the air/water interface. Such layers can easily be removed. On the other hand, if oil is present as a dispersed phase in the form of fine droplets (oil in water emulsions), separation is much more difficult. Many emulsions are stabilised with surfactants or other emulsifying agents. Modern emulsions often contain droplets, which are very small (size range of less than 10 microns) and stabilised with powerful emulsifying agents. De-emulsification and oil extraction from such systems present particular challenges. Moreover, such processes have to be economically feasible to be accepted by industry.

Sedimentation is one of the favourite gravity-separation methods to remove contaminants in water treatment. Most oils have low density and cannot be separated by sedimentation from water streams. On the other hand, flotation is a much more suitable technique to remove oil from water during or after de-emulsification. Flotation is a process in which one or more specific particulate constituents of a slurry or suspension of finely dispersed particles or droplets become attached to gas bubbles so that they can be separated from water or other constituents. Gas/particle aggregates float to the top of the flotation vessel where they are separated from water and other unfloatable constituents.

One of the key steps in the flotation method is the introduction of air bubbles into water. In early flotation machines, coarse bubbles (2–5 mm) were introduced into the contaminated water by blowing air through canvas or other porous material. In some impeller-based machines, air could be introduced from the atmosphere without compressors or blowers. This type of flotation, in which impeller action is used to provide bubbles, is known as Induced-Air Flotation (IAF) and also produces fairly coarse bubbles. Such flotation methods are not suitable for wastewater treatment and oil extraction. Jameson (Clayton et al., 1991) developed an improved version of IAF, which was more successful in the removal of fats, oil, and grease from wastewater. Another flotation method, called Dissolved Air Flotation (DAF), is much more common in the treatment of oily wastewater (Bratby and Marais, 1977; Kiuru, 2001). In DAF, a stream of wastewater is saturated with air at elevated pressures up to 5 atm (40–70 psig). Small bubbles are formed, and continuously flowing particles are brought into contact with bubbles. There is a price to pay for having such small bubbles (up to 20 microns): Such bubbles rise very slowly to the surface of the tank. This is the main reason for the large dimensions for DAF tanks. Final solubility of gas in water, even at high pressures, also results in fairly low air-to-water ratios. Air-to-water ratios of 0.15:1 by volume are common in DAF systems, and it is very difficult to achieve higher ratios.

One of the recent developments in flotation technology circumvented some of these problems. In particular, the Air-sparged Hydrocylone (ASH) couples a porous cylindrical membrane with design features of a hydrocyclone (Miller, 1981). Gas is introduced through the porous membrane while wastewater is pumped through the hydrocyclone. Such a device is not dependent on the gas solubility and can introduce air-to-water ratios as high as 100:1. Because the bubbles are sheared off the wall of the porous membrane due to the high velocity and centrifugal forces inside the hydrocyclone, they are broken up into very small sizes comparable to those observed in the DAF. Thus, even though the ASH is essentially a mechanically sparged device similar to the IAF or early flotation devices, it does not suffer from similar problems. The ASH is one of the first centrifugal flotation techniques that was developed and applied in the treatment of wastewater. The ASH and other Centrifugal Flotation Systems (CFS) will be described in this manuscript.

Because the ASH is essentially a modified hydrocyclone device, it has similar restrictions. Removed particulates in such devices are forced through an overflow device known as the vortex finder. In the ASH, the creation of an overflow results in a separate stream of contaminated water with a low concentration of solids. This deficiency results in sludge with low particulate concentrations and a larger volume of waste.

Below, we discuss modifications to the ASH device. Bubble Accelerated Flotation (BAF) evolved from ASH technology to address operational limitations resulting from the traditional stream-splitting characteristics of hydrocyclones. BAF no longer incorporates a cleaned-water underflow restriction that forces the froth and contaminants to be ejected through a vortex finder. Removing the underflow restriction in the BAF improves the consistency and ease of operation. When the stream exits the BAF hydrocyclone, the bubble/particle aggregates have already formed, and coagulation and flocculation are complete before the froth particles are ejected with the cleaned water through the underflow. The requirement to separate this froth in the receiving tank from the treated water results in the new BAF system described below.

2 Bubble Accelerated Flotation (BAF) system

2.1 Description and principles of operation

The BAF system consists of a bubble chamber and a BAF tank (see Figures 1–3). The bubble chamber can be operated with sparged air, induced air, vacuum, electro-flotation and even dissolved air. We will first describe the air-sparged bubble chamber and BAF system. Such systems are commercially installed and successfully operated in over 20 locations within the USA. See Morse et al. (2000, 2001), Owen et al. (1999) and Colic et al. (2001) for detailed descriptions of this system. Figures 1 and 3(a) show illustrations of the air-sparged bubble chamber. Wastewater is introduced through a liquid/liquid hydrocyclone head (tangential injection) at the top of the unit. The tangential inlet creates a swirl flow and causes centrifugal acceleration as the water is forced into a swirl layer against the inner wall of an inert porous tube. A gas plenum, which encloses the porous tube, is pressurised commonly with low-pressure air from a blower. The air pressure must slightly exceed the water pressure due to the centrifugal acceleration and the resistance of the tube itself. Gas forced through the tube generates bubbles on the inside surface that are extremely buoyant in the centrifugal field because of the effective radial pressure gradient in the swirl layer generated by the hydrocyclone action. The bubbles accelerate toward the inner surface of the swirl layer. In addition to creating the radial acceleration of the bubbles, the centrifugal field also aids in the classification of particles with densities different from that of water. The acceleration across the swirl layer usually ranges from 25 Gs to 1,000 Gs during routine operation. Even though the residence time of the liquid stream in the bubble chamber is only a fraction of a second, due to their rapid acceleration, the bubbles traverse the short distance across the swirl layer (typically 1 cm for a 15-cm diameter unit) in milliseconds. During this time, the bubbles collide with particles moving toward the porous tube and form bubble/particle aggregates. Another advantage of the sparging gas is that it cleans and protects the porous tube from scaling and fouling.

Given the small bubble size, large bubble flux, and the kinetic paths of the bubbles through the swirl layer, gas transfer rates are very high. This results in the ability to remove volatile organic species or to aerate the water if desired.

The flotation process is completed outside the bubble chamber in the BAF tank. In a DAF system, the tank is designed to allow sufficient residence time for the bubbles and particles to collide and for the resulting aggregates to rise to the surface. This results in a requirement of low hydraulic flow rates in order to permit bubble/particle aggregates to form and to float to the surface without being swept out of the system. In DAF systems, the low hydraulic flow rate is accomplished by increasing the cross-sectional area of the flow and consequently enlarging the tanks. Consequently, for the DAF there is a trade-off between footprint and residence time.

The design needs for BAF separation tanks are completely different (Desam et al., 2001). The bubble chamber has already created bubble/particle/polymer aggregates before they enter the tank. The tank is simply used as a separator and not to achieve bubble/particle contact. Unlike other flotation tanks, the effluent from the bubble chamber can enter the tank above the water level, resulting in a shorter distance for the froth to reach the surface. This feature, combined with the fact that the aggregates are already formed, permits much higher hydraulic flow rates through the flotation tank. Figure 2 illustrates the BAF tank with the bubble chamber attached.

Figure 1 Cut-away view of a bubble chamber

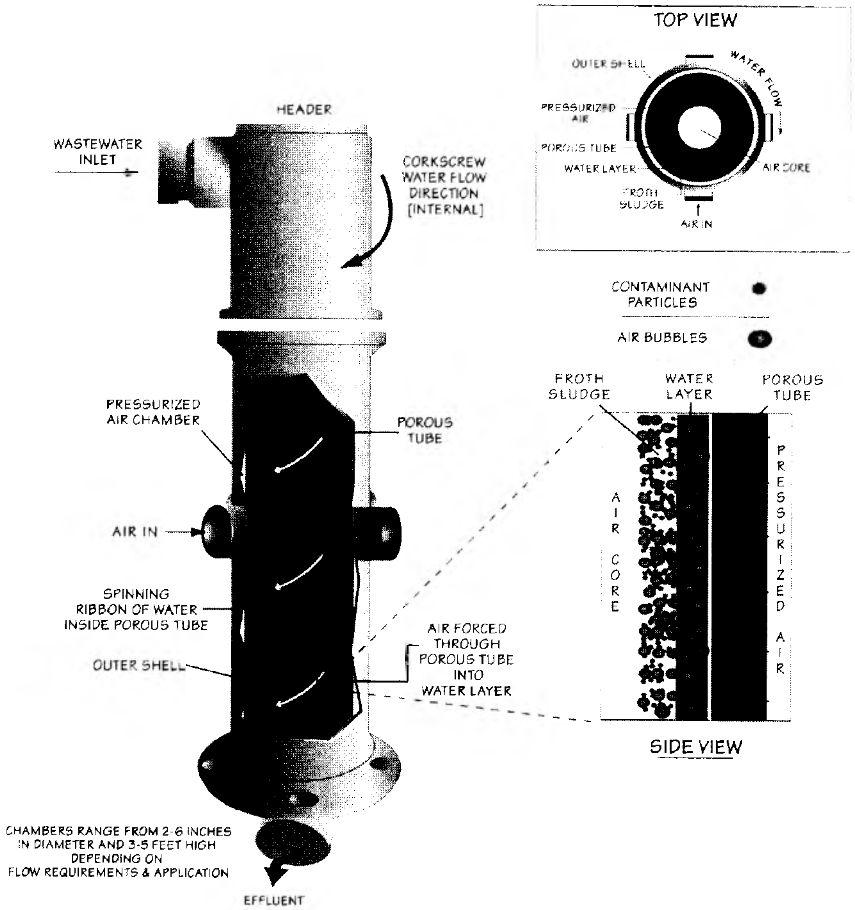
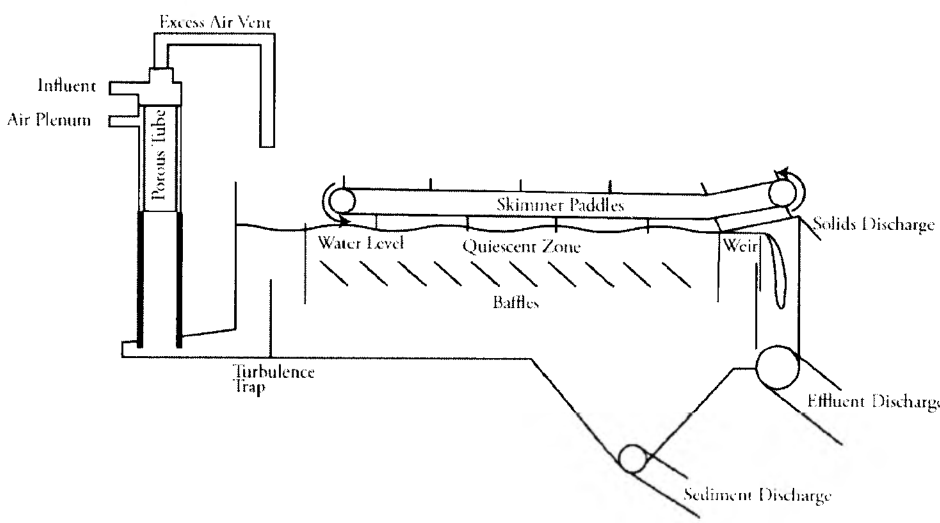


Figure 2 Cut-away view of a Bubble Accelerated Flotation (BAF) tank



In addition to the air-sparged bubble chamber, we recently developed an induced-air bubble chamber, vacuum flotation bubble chamber, and electro-flotation bubble chamber. In the induced-air bubble chamber, the top of the bubble chamber is open and in contact with the air, as shown in Figure 3(c). This configuration enables the vortex turbulence formed inside the bubble chamber to be used to mix in air from the environment. This obviates the need for expensive air blowers and sparge tubes, which get fouled. If the top of the bubble chamber tube is closed, the vortex inside the tube creates a vacuum that helps nucleate air bubbles of very small size. Such a system is shown in Figure 3(b). Finally, if a helical coil made from conductive material such as platinised titanium or stainless steel is placed inside the tube of the bubble chamber, electric current can be used to electrolyse wastewater and produce fine hydrogen and oxygen bubbles. If chloride is present in the water, some chlorine can also be released, which helps in disinfection. An electro-flotation BAF is shown in Figure 3(d).

2.2 *BAF applications*

Examples of installations and performance data for the air-sparged BAF are outlined in Table 1. There are currently more than 20 systems installed within the continental USA. The advantages of the system are small footprint, high performance, high solids loading in the sludge, and low amount of treatment chemicals used. The technology is particularly efficient in the removal of free and emulsified Fats, Oils, and Grease (FOG). Following successful flocculation, the BAF system can also be used to remove low-density submicron particles such as latex particles used in screen-printing of fabrics. The BAF system has also been used to remove totally hydrophilic particles such as zeolites or quartz. The BAF system has a much shorter response time to changes in chemistry (seconds as opposed to hours in clarifiers or DAF). This is very useful in wastewater treatment, as the composition of incoming water often changes, and adjustments must be made quickly.

Figure 3 Cut-away view of (a) air sparged bubble chamber; (b) vacuum bubble chamber; (c) induced-air bubble chamber and (d) electro-flotation bubble chamber

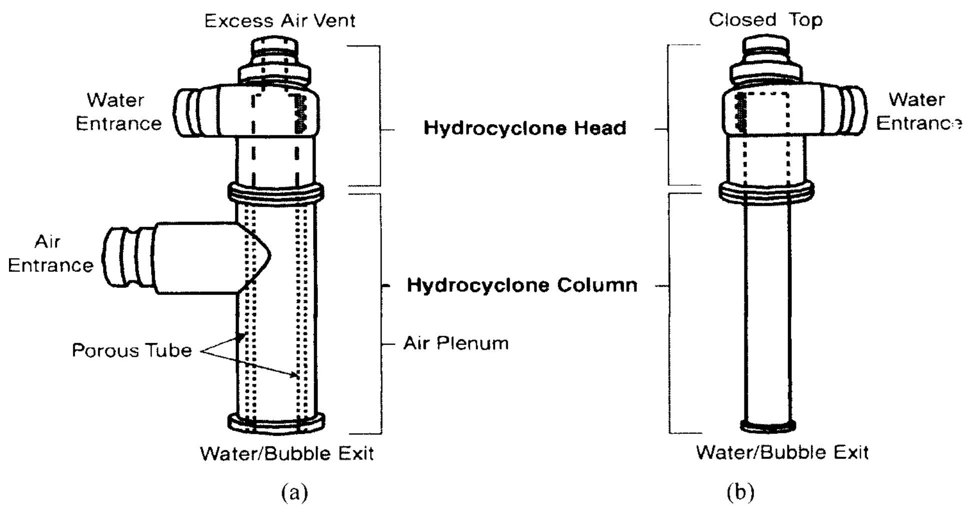
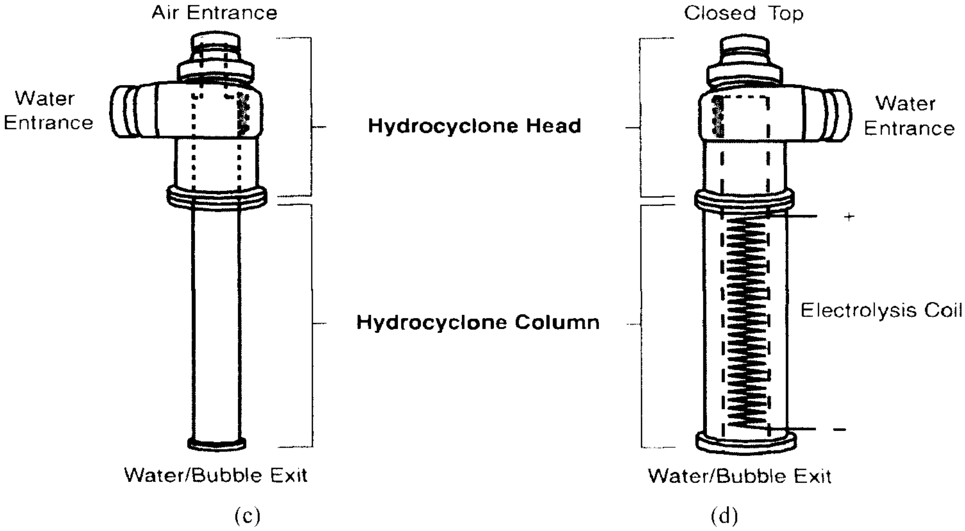


Figure 3 Cut-away view of (a) air sparged bubble chamber; (b) vacuum bubble chamber; (c) induced-air bubble chamber and (d) electro-flotation bubble chamber (continued)



Numerous approaches were used to coagulate and flocculate particulates in wastewater prior to the BAF treatment. The pH of the suspension is usually adjusted close to the pH of the isoelectric point to reduce consumption of coagulants (charge neutralising agents). The residual charge is then partially neutralised with either inorganic coagulants or low-molecular-weight cationic polymers (polyamines, polyDADMACs etc.). Dual-polymer flocculation with High-Molecular-Weight (HMW) cationic and anionic Polyacrylamide Flocculants (PAMs) is then performed. Dual-polymer flocculation with HMW PAMs yield large, stable flocs, which float very efficiently inside the BAF tank. We also observed that if the main portion of the charge is neutralised with low-molecular-weight cationic coagulants, the BAF performance is not as good. Among the most efficient polymeric flocculants used were Cytec's C-498 HMW cationic polyacrylamide with ultrahigh-molecular-weight (>5,000,000 D) and 0.55 charge density and Cytec's anionic polyacrylamide A-130 HMW with-molecular-weight estimated to be over 7,000,000 D. When animal feed applications of the collected sludge are desired, Cytec's 'GRAS' (generally regarded as safe) polymers, such as 234 GDH cationic moderate-molecular-weight polyacryalamide, are used. When necessary, emulsion polymers have also been used with the BAF system. Dual-polymer flocculation generally results in very low residual polymer concentration in the effluent. This is particularly important when flotation is used as a pretreatment ahead of membrane separation processes. Membranes are particularly sensitive to fouling with cationic polymers.

Table 1 Examples of full-scale operating installations of BAF flotation systems

		BAF™ performance classified by industry								
Location	*Process*	*BOD before* (mg/l)	*BOD after* (mg/l)	*BOD removal* (%)	*TSS before* (mg/l)	*TSS after* (mg/l)	*TSS removal* (%)	*FOG before* (mg/l)	*FOG after* (mg/l)	*FOG removal* (%)
Meat and seafood processors										
Los Angeles, CA	Seafood	3190	1308	59	1675	67	96	n/a	n/a	n/a
Westport, WA	Seafood	1375	564	59	484	189	61	166	25	85
Salinas, CA	Renderer	1000	300	70	800	80	90	300	30	90
Denver, CO	Renderer	n/a	n/a	n/a	600	60	90	560	28	95
Klingerston, PA	Egg product	656	210	68	391	133	66	n/a	n/a	n/a
West Liberty, IA	Turkey	600	210	65	532	133	75	n/a	n/a	n/a
Kent, WA	Meat	1882	320	83	1120	56	95	1100	22	98
Food processors										
Los Angeles, CA	Mayonnaise and salad dressing	11925	954	92	7500	75	99	n/a	n/a	n/a
Tennessee	Salad dressing and vegetables	12083	2900	76	3000	150	95	n/a	n/a	n/a
Madera, CA	Olive processor	2200	1100	50	1000	50	95	316	95	70
Modesto, CA	Corn and potato	335	672	77	250	50	98	n/a	n/a	n/a
Denver, CO	Corn and potato	2958	710	76	1960	98	95	n/a	n/a	n/a
Umatilla, OR	Onions	1099	747	32	540	54	90	n/a	n/a	n/a
Hilmar, CA	Dairy	2900	1450	50	1500	75	95	266	80	70
Laundry and wash facilities										
Los Angeles, CA	Pre-wash and dye	489	318	35	416	50	88	n/a	n/a	n/a
Fresno, CA	Wash-rack	n/a	n/a	n/a	n/a	n/a	n/a	400	20	95
Lexington, KY	Laundry	347	250	28	450	45	90	n/a	n/a	n/a

It was also observed that high-molecular-weight polymeric flocculants can be added directly into the bubble chamber head. Large batch mixing tanks or floc tubes can therefore be avoided. Powerful vortex mixing and wall effects inside the bubble chamber tube result in better uncoiling of polymers with minimum polymer and floc breakage. HMW flocculants can therefore achieve superb flocculation inside the bubble chamber.

This often results in the formation of large flocs with diameters of up to 10 cm. The flocs are very stable, with high solids loading of between 10% and 30% upon short drainage. The best flocs are usually produced when using a combination of HMW cationic and anionic flocculants. Fan et al. (2000) show that dual-polymer flocculation actually results in more efficient uncoiling of the HMW polymeric flocculants. The uncoiled flocculant chains then act as better bridging agents. Vortex mixing inside the centrifugal field within the bubble chamber seems to enhance this process. Additional research should be performed to investigate these processes.

3 Dissolved-air-centrifugal flotation: the Gas Energy Management (GEM) system

3.1 Description and principles of operation

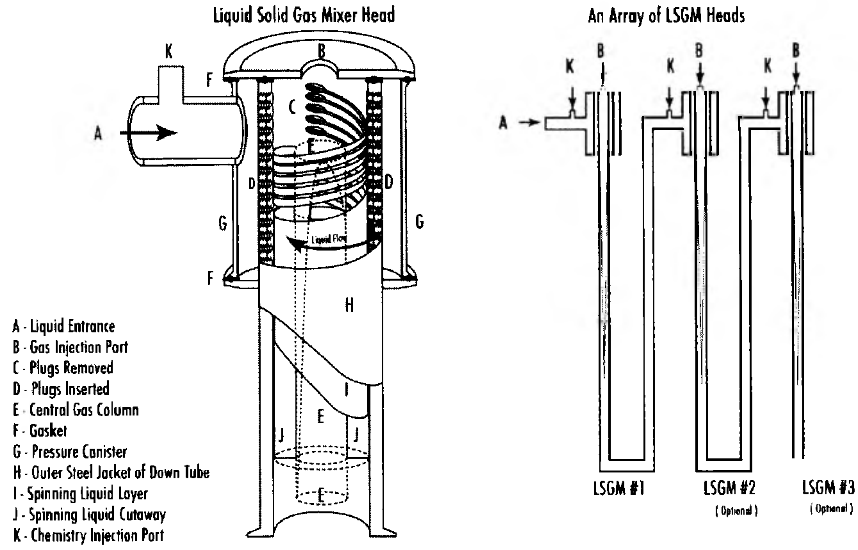
As mentioned in the introduction, in DAF, bubbles are formed by a reduction in pressure of water pre-saturated with air at pressures higher than atmospheric and up to 100 psi. The supersaturated water is forced through needle valves or special orifices, and clouds of bubbles 20–100 microns in diameter are produced. Yet, to avoid clogging of such orifices with particles, only 20% of already cleaned water is pressurised and recycled to the wastewater stream. This results in a low-energy mixing of the main wastewater stream and the bubble stream. Treatment chemicals, coagulants and flocculants have to be added in mixing tanks upstream. As already described earlier, floc separation happens in this tank, which requires quiescent conditions and a large footprint.

We proposed that a more efficient flotation system could be developed by combining high-energy centrifugal mixing of a liquid cyclone system (we termed it the Liquid Cyclone Particle Positioner, LCPP) with dissolved air as a source of flotation bubbles. As in the case of BAF, coagulants and flocculants can be delivered in situ directly into the flotation unit. The bubble chamber was replaced with the LCPP for more efficient mixing of treatment chemicals, which occurs during bubble formation and nucleation. Such a procedure results in flocs which are very porous and loaded with entrained and entrapped air.

As shown in Figure 4 the LCPP also acts as a Liquid-Solid-Gas Mixer (LSGM). Replacing the classical hydrocyclone head with the LCPP provides extremely energetic mixing by sequentially transporting liquid and entrained particles and gas bubbles throughout a centrifugally rotating liquid layer. Microturbulence in such vortices results in all particles and bubbles down to colloidal and molecular size acting as little mixers. Axial and radial forces inside the LCPP help mix coagulants and flocculants with the particles. Uncoiling of the polymer and better mixing of ultrahigh-molecular-weight polymers is achieved in the LCPP. As explained in the previous section, such efficient mixing is important for proper flocculation of suspended particles.

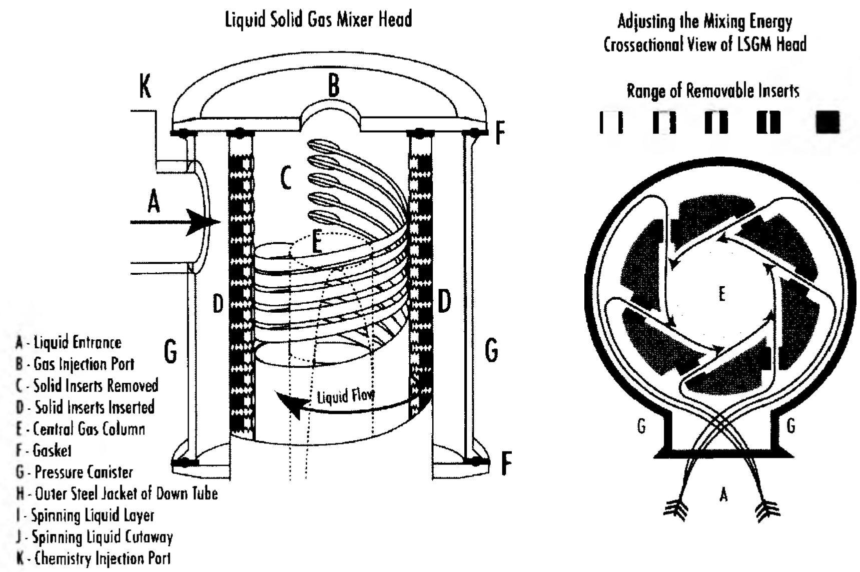
Further modification of LCPP heads, as opposed to hydrocyclone heads, introduced multiple holes with plugs inside the LSGM heads, as shown in Figure 5. By changing the number of plugs, we can modify the mixing energy and head pressure from very low to very high. In this way, we can mix low-molecular-weight coagulants at relatively high energy and high-molecular-weight flocculants at relatively medium and low mixing energy to promote final large floc formation.

Figure 4 Cut-away view of (a) liquid solid gas mixer head and (b) an array of liquid solid gas mixer heads



(a) (b)

Figure 5 Cut-away view of (a) liquid solid gas mixer head and (b) cross-sectional view of a liquid solid gas mixer head, illustrating the method for adjusting mixing energy

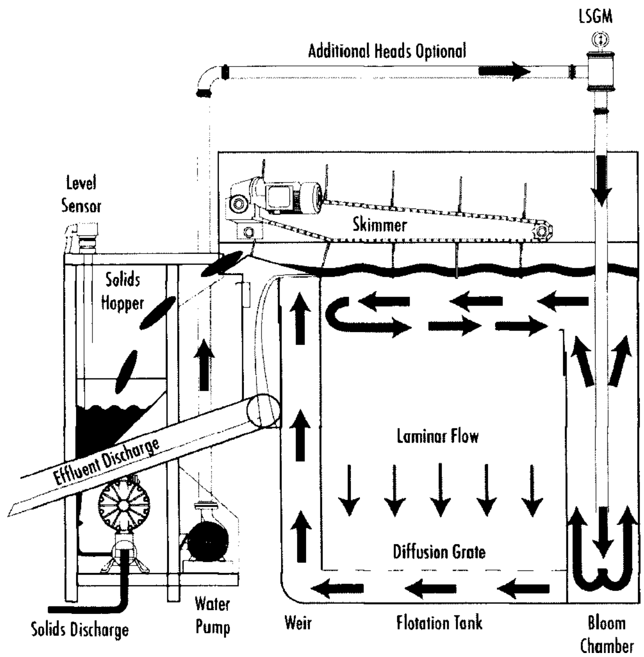


(a) (b)

Figure 6 presents a schematic of the GEM flotation system. It should be noted that for the sake of clarity only one LSGM head is presented. If more treatment chemicals are added, the LSGM head can be used to properly mix every additional chemical at its proper mixing energy (one mixing head per addition). Water and gas are introduced into the

LSGM on top and pumped through the LCPP chamber. After rapid mixing (seconds), pressure is released with the cavitation plate. Nucleating bubbles and flocs are well mixed. As mentioned before, this results in the formation of large flocs full of entrained and entrapped air. Such flocs are already separated from water inside the LCPP nucleation chamber. As flocs enter the tank, they rise quickly to the top where they are skimmed and sent to solids dewatering devices.

Figure 6 Cut-away view of the gas energy managed mixing system



As compared to the ASH and BAF, the GEM system uses less energy, since there is no need for air blowers for air sparging. This also results in less noise. Controlled mixing energy produces stable flocs with much less carryover and higher solids loading. The footprint for this system is still only 10–20% of the classical DAF or clarifier devices. A blanket of small bubbles inside the tank acts as a 'gas filter', filtering out clean water while preventing the transport of small pinpoint flocs into the clean water stream. Also, when wastewater with surfactants is treated, for some reason no foaming occurs inside the GEM system. Finally, it is possible to install sensors close to the nucleation chamber and observe any disturbance in flocculation performance almost instantaneously. This can be used to install turbidity-driven chemical-additive dosage-control systems. Such systems can save significant amounts of money and produce a better quality of outgoing wastewater effluent. A detailed description of the GEM system can be found in Morse et al. (2004).

3.2 Applications of GEM system in wastewater treatment

As mentioned previously, the GEM system is particularly efficient in the treatment of wastewater with high solids loading (higher than 10,000 ppm of TSS). The GEM system was tested in the treatment of such oily wastewater from fish processing plants, rendering plants, snack-food processing plants, and salad-dressing processing plants. Water with up to 70,000 ppm of TSS and 150,000 of CODs was treated, and the TSS was reduced below 100 ppm, the CODs below 15,000 ppm, and complete removal of the FOGs was achieved. The GEM system is currently being tested as a polishing tertiary treatment before membrane separation. In such applications, where very low concentrations of TSS and FOGs are present (less than 10 ppm), the system shows great promise. Further, the GEM system was successful in removing TSS and FOG from fish-processing plants that use sea water with very high conductivity (up to 50,000 micromhos/cm). Appropriate proprietary chemistry had to be used to flocculate particles and FOGs at such high ionic strength, under which conditions polymeric flocculants are difficult to uncoil. Positively charged coagulants such as aluminum sulphate were used to overcharge negatively charged solids. Then ultrahigh-molecular-weight, medium charge anionic emulsion flocculants, such as A-4816 from Cytec Corporation (molecular weight 40,000,000 D, 30% charge), were added to achieve bridging flocculation. LCPP mixing might have helped in the polymeric flocculant uncoiling process. Further research will test such a hypothesis. Performance of the GEM system is documented in Table 2.

Table 2 Examples of pilot plant and full – scale operating installations of GEM flotation systems

Wastewater	*TSS before* (ppm)	*TSS after* (ppm)	*COD before* (ppm)	*COD after* (ppm)
Seafood processor	3,500	120	27,000	10,000
Seafood processor	28,000	150	62,000	12,000
Rendering plant	25,000	80	67,000	13,000
Food processing	1,500	35	12,000	3,000
Municipal	285	50	320	180
Juice processing	385	10	9,000	5,500
Salad dressing	120,000	50	150,000	12,000
Jeans washing	30	3	100	60
Laundry	5,500	5	24,000	3,500
Snack food plant	45,000	55	130,000	10,000

Seafood processing and rendering wastewater had very high salt concentration (conductivity 50,000 micromhos/cm).

In spite of many advantages, the high-throughput, high-efficiency CFS have their problems. Air-handling pumps as well as modified centrifugal pumps for such flotation systems use more energy when compared to classical DAFs. Closer tolerances of such pumps or heads of LSGM in the GEM system require good screening to remove large particles such as sand that can cause wear and reduce pump lifetime. To achieve the above-described high removal efficiency of contaminants and sludge with high solids loading, high-molecular-weight polymeric flocculants have to be used. However, the ability to clarify wastewater with high efficiency and handle waste streams with ultrahigh solids loading makes such systems very attractive for the treatment of industrial wastewater streams or as a pretreatment ahead of membrane separation or bioreactor systems. Future studies will show just how cost-effective they can be in municipal sludge-thickening applications.

4 Other Centrifugal Flotation Systems (CFS)

Swirl flow of fluids and mixing with coagulants, flocculants, and air bubbles occurs inside the ASH and other derived CFS. Several versions of inverted ASH with upward water flow have been reported. Hydrocyclone flotation systems with induced or dissolved air have also been tested. All these techniques incorporate a vortex finder similar to the classical ASH with the attendant problems discussed earlier. The advantage of such techniques is that they do not use large separation tanks. This results in a smaller footprint and reduced cost of equipment compared to BAF, DAF, and IAF.

Modified versions of the jet (Jameson cell) flotation system have also been developed and applied. In a recent advancement of the Jameson cell technology, a new 'low shear' method is used to mix the air, untreated wastewater, and flocculants. As in the previously described induced-air BAF system, untreated wastewater and flocculants are gently introduced into the top of the cylinder used for centrifugal mixing (termed the downcomer for Jameson cell systems). A portion of the clean effluent is recycled back into the top of the downcomer. The recycle effluent passes through an orifice, accelerating the liquid to produce a simple liquid jet. The kinetic energy of the jet results in air being entrained into the downcomer in much the same way as air might be entrained into a bucket of water using a hose. Air is dragged down into the liquid and broken up into small bubbles by the turbulence in the top of the downcomer. The Jameson cell thereby utilises the energy of the fluid to induce air into the cell, rather than requiring an external compressor or blower. As in the case of the BAF system, the presence of air bubbles at the time of flocculation is extremely beneficial, as it results in the bubbles being entrapped with the actual floc structure. The incorporation of bubbles in the floc structure provides buoyancy and allows particles to be floated independent of their surface characteristics. The downward velocity of the bubble/liquid mixture in the downcomer is designed such that all bubbles have to descend and emerge into a reservoir (or cell) at the bottom of the downcomer. The reservoir acts as a disengagement zone, allowing the aerated floc structures to float to the surface to form a sludge layer. As in the case of BAF and GEM, separation already happens inside the centrifugal force column (in this case downcomer). The sludge overflows the reservoir into a launder, whilst the cleaned effluent passes to the next stage in the process.

Other modifications of jet flotation include the DAF jet (dissolved-air mode) and addition of one more cylinder around the downcomer to lead separated flocs towards the top of the separation tank (Feris et al., 2004). While these modifications increase the cost and result in a more complicated system they also increase the separation efficiency.

Another turbulent in situ centrifugal flotation system, termed FF, was recently developed (da Rosa and Rubio, 2005). As in the case of GEM, BAF, and the modified jet-flotation cell, polymer and air are added at the same time inside a centrifugal mixing system. Dissolved air is used for smaller bubbles. As in the case of BAF and the GEM system, large flocs entrained with air develop when high-molecular-weight flocculants are used. Multiple cylinders around the downcomer are used, similar to the modified jet-flotation cell. The air excess leaves through the centrifugal cylinders at the top, and the flocs float very fast within seconds after leaving the downcomer cylinder. A novel flocculation and helical mixing system has also been developed by the same group (Carissimi and Rubio, 2005).

5 Summary and conclusions

Wastewater treatment depends on many interdependent factors. These factors should be carefully considered when selecting and designing integrated water-treatment systems. Flotation devices are an excellent choice for treatment of water contaminated with fats, oils, and grease, as well as particles with low density and particulates with tendencies to float rather then sediment, such as algae or biological sludge.

Total flow of wastewater to be treated per day and peak flows at different times of day are to be taken into account when selecting a flotation system. For large flows and low contaminant loads at municipal wastewater treatment plants, classical DAF devices are still the best choice. DAFs can be scaled up to flows of more than 20 m^3/min. Centrifugal flotation devices perform well at low and medium flows (20 l/min to 3 m^3/min). Such systems are particularly efficient for treatment of industrial wastewater with high loads of suspended solids (TSS more than 5000 mg/l) and high loads of FOGs (more than 500 mg/l). Centrifugal systems have so far not been tested for sludge-thickening applications. CFS have been quite successful in treatment of food-processing wastewater (snack-food preparation, dairy, rendering, chicken, beef, poultry processing, bakeries, breweries, sausages, sauces, mayonnaise, vegetable processing, fruit and juice processing, desserts, fish processing, corn food, potato food, etc.). Application of CFS in the treatment of petroleum, automotive, washracks, laundry, and textile wastewater has also been described.

Flotation system size (footprint) for a given flow of wastewater is commonly described in terms of Hydraulic Loading Rates (HLR). In the SI system, the units of m^3/h for flow and m^2 for equipment size are used; therefore, HLR units are m/h (flow divided by equipment area). The HLR values for various flotation systems are summarised in Table 3. The DAFs used in wastewater treatment usually have a low HLR, between 5 m/h and 50 m/h. CFS can operate at HLRs that are an order of magnitude higher; therefore, such systems have a significantly lower space requirement. Additional space savings are achieved by in situ flocculation within the centrifugal mixing devices. As described earlier, fast mixing and flocculation in such systems occurs in seconds, as opposed to minutes in classical flocculation tanks.

Table 3 Average hydraulic loading rates (m/h) for some flotation devices used in wastewater treatment systems

Flotation technique/system	*Hydraulic loading rate* (m/h)
IAF	30–500
DAF	5–50
Jet flotation	50–350
ASH	100–800
BAF	20–400
GEM	20–350
FF	140–2000

IAF: Induced-Air Flotation; DAF: Dissolved Air Flotation; ASH: Air Sparged Hydrocyclone flotation; BAF: Bubble Accelerated Flotation; GEM: Gas Energy Management flotation; FF: Flocculation–Flotation.

The concentration of solids (solids loading) in the produced sludge is another important parameter to consider when choosing the appropriate equipment/strategy for solid/liquid separations in wastewater treatment. DAFs produce sludge with solids loading between 1% and 6%. CFS produce sludge with up to 20% solids. Ironically, this may produce a problem, since such sludge is very viscous and dries fast. Adequate pumps and sludge disposal equipment should be available; otherwise, sludge has to be diluted for further processing. More research is needed in how to efficiently remove concentrated sludge without disturbing the bottom layer and causing the transport of particulates into the clean water product (Bratby et al., 2004). No matter how efficient flocculation may be, incomplete transport will decrease the performance of the flotation system.

Average bubble size, size distribution, bubble stability, and rise time in tanks are also important parameters for flotation systems. Average bubble sizes for some common flotation devices are summarised in Table 4. Centrifugal forces inside CFS further reduce the average bubble size. Detailed measurements of average bubble size in the ASH system compared to bubbles produced with air sparging only, showed bubbles with almost an order of magnitude smaller diameter. Jet flotation also produces bubbles with average sizes that are 2–4 times smaller than those produced in other IAF systems. As explained previously, centrifugal forces in the CFS induce solid/liquid separation inside the chamber before water even enters the separation tank. Therefore, rise time for solids and bubbles inside tanks is much shorter, comparable to non-centrifugal flotation systems.

CFS offer an alternative to traditional DAF with several advantages. The CFS float contaminants more effectively than DAF, because all wastewater is treated in the centrifugal contactor. Centrifugal forces provide for very efficient mixing of contaminants, bubbles, and treatment chemicals. The hybrid dissolved-air CFS such as GEM are particularly effective. The efficient mixing action inside the LCPP head means that very high-molecular-weight polymeric flocculants can be used for treatment. The tanks included in GEM systems are considerably smaller in volume and footprint than DAF tanks. This leads to savings in material costs and land usage. The fast response time of the GEM system (seconds) is also convenient for rapidly changing industrial wastewater influent treatment (online chemistry dosage sensors). GEM systems have been installed and operated in a number of situations, of which only a few are mentioned here as examples. The GEM system performs exceptionally well for removal of FOG from industrial wastewater. However, removal of colloidal particles, including hydrophilic materials such as quartz, is also very efficient. Removal rates of over 99% of Total Suspended Solids (TSS), 80% of Chemical Oxygen Demand (COD), and 95% of FOG (over 99.5% of suspended emulsified FOG) are not uncommon. Soluble contaminants such as heavy metals or organics can also be removed if precipitated or adsorbed. The system operates best when used with the dual-polymeric flocculants to aggregate suspended particulates. In situ ultrafast coagulation and flocculation occur within the LCPP, with no need for additional tanks. Modular mixing energy application inside the LCPP can mix low-molecular-weight coagulants at relatively high energy and high-molecular-weight flocculants at relatively medium or low mixing energies. The GEM system can be used to treat wastewater with up to 100,000 ppm of TSS, which is much higher than that treated by DAF. Other CFS such as FF or modified Jameson–jet flotation offer similar advantages. In spite of their many advantages, the above-described high-throughput, high-efficiency flotation systems have their problems. Air-handling pumps as well as modified centrifugal pumps use more energy when compared to classical DAFs. Closer tolerances of such pumps or heads of LSGM in the GEM system require good screening to remove large particles such as sand that can cause wear and reduce pump lifetime. To achieve the high removal efficiency of contaminants and sludge with high solids loading, more expensive high-molecular-weight polymeric flocculants have to be used in systems such as GEM or FF. Development of coagulant and flocculant dosage systems that respond to changes in wastewater properties is also needed to fully automate such systems without loss of efficiency.

Table 4 Average bubble size reported for some flotation systems used in wastewater treatment

Flotation technique/system	*Average bubble size* (μm)
IAF	1000
DAF	20–50
Jet flotation	300–600
ASH	80–200
GEM	15–40
FF	100
EF	15
CAF	30–200

IAF: Induced-Air Flotation; DAF: Dissolved Air Flotation; ASH: Air Sparged Hydrocyclone flotation; GEM: Gas Energy Management flotation;
FF: Flocculation–Flotation; EF: Electro Flotation; CAF: Cavitation Air Flotation.

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